Citation for published version:
Agar, AS, Goodfellow, MJ, Newnes, LB & Goh, YM 2019, 'Stakeholder perspectives on the cost requirements of Small Modular Reactors', *Progress in Nuclear Energy*, vol. 112, pp. 51-62.
https://doi.org/10.1016/j.pnucene.2018.12.006

DOI:
10.1016/j.pnucene.2018.12.006

Publication date:
2019

Document Version
Peer reviewed version

Link to publication

Publisher Rights
CC BY-NC-ND

University of Bath

Alternative formats
If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Download date: 05. May. 2023

*Revised Manuscript
Click here to view linked References

Title: Stakeholder Perspectives on the Cost Requirements of Small Modular Reactors

Author names and affiliations: Amritpal Singh Agar[a*], Martin J Goodfellow[b], Yee Mey Goh[a], Linda B Newnes[c]

[a]Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University

[b]Rolls-Royce Plc

[c]Department of Mechanical Engineering, University of Bath

*Corresponding author contact via email: a.s.agar@lboro.ac.uk, Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Epinal Way, LE11 3TU, United Kingdom

Highlights:

- Nuclear power cost experts are consistent in their understanding of what will impact on the commercial success of a near-term deployable SMR.
- Stakeholders from different lifecycle stages were interviewed to elicit their preferences on SMR cost characteristics.
- AHP with expert elicitation is used to rank the relative importance of cost factors influencing the LCOE.
- Project financing is ranked as the most important cost factor influencing the commercial success of the SMR.
- Further research is required to understand the interdependencies between cost factors influencing the LCOE.

Declarations

Declarations of interest: none

Abstract:

The cost of a nuclear power plant (NPP) is an important influence on the future commercial success of Small Modular Reactors (SMRs). At the early design stage, the cost requirements of SMRs can be derived from an analysis of the factors driving the Levelized Cost of Electricity (LCOE). It is often much later into the development process before customers are engaged and their cost requirements are known, by which time key design decisions which influence the lifecycle cost have already been locked-in. A clear understanding is required of the cost priorities for the key stakeholders who are to invest in the SMR.

This paper presents a novel approach to ranking the relative importance of different cost factors used to calculate the LCOE. Using a dynamic stakeholder analysis, the key decision-makers for each stage of the SMR product lifecycle are identified. The Analytic Hierarchy Process (AHP) with pair-wise comparisons obtained from nuclear cost experts is employed to rank the different factors in terms of their relative importance on the commercial success of a near-term deployable SMR. Each expert provides a different set of rankings, although project financing cost is consistently the most important for the successful commercial deployment of the SMR. The approach presented in this paper can be used as a verification method for any power generation technology to provide confidence that cost requirements are adequately captured to design for life cycle cost competitiveness from the perspective of different stakeholders.

Keyword List: Levelized Cost of Electricity, Small and Modular Reactors, Nuclear Power Plants, AHP, Stakeholder

1 Introduction

In 2015 the UK Government announced a £200million competition to support the development of small reactor technology for deployment as part of the future energy mix. Although no vendor was selected for the competition, in June 2018 the Government announced the “Nuclear Sector Deal” (Beis, 2018b), proposing support for Advanced Modular Reactors (AMRs) as a long-term energy solution. AMRs are advanced reactors which use new or novel cooling or fuel systems based on Generation IV technology. These have additional functionality such as co-generation of heating or water desalination. Defined separately to AMRs, Small Modular Reactors (SMRs) are considered a more near-term deployment solution based on conventional advanced light water reactor (LWR) technology used in existing large Generation III Nuclear Power Plants (NPPs), but smaller in scale (Beis, 2018a).

In liberalized markets the development and investment in SMRs depends upon the economic competitiveness of a design when compared with other power generation options (Vegel & Quinn, 2017; Kidd, 2013). SMRs are likely to have a reduced upfront total investment cost (Carelli et al, 2007) introducing the flexibility to allow series construction of multiple small units, providing a more manageable cash flow profile (Ingersoll, 2009). It is expected that greater emphasis on factory production and the design of smaller, standardised components, will introduce greater certainty of reducing construction cost and schedule utilising manufacturing learning and by minimising site work (Cooper, 2014).The financing of an SMR then becomes easier and potentially less risky, resulting in a lower cost of capital (Ramana & Mian, 2014). Conversely, the SMR will also have to maximise availability, capacity factor and fuel utilisation to maintain competitive operational performance (Hidayatullah et al, 2015).

There are currently more than 50 small reactor designs at various stages of development around the world with many potential applications (Carelli & Ingersoll, 2014). Different designs have different characteristics, related to technology, physical size, electrical output and operating parameters. No single SMR concept resolves all the problems identified with LRs (Ramana & Mian, 2014). For more novel SMR designs, issues regarding the verification and validation of unproven technology, the need for new training regimes and additional research and development activities have been highlighted as key to overcoming their commercialisation limitations (Hidayatullah, et al, 2015). Other studies have assessed the strategic and economic competitiveness of SMRs from a systems view, considering SMRs as one of a portfolio of power generating technologies from the perspective of a utility, as part of the national infrastructure and incorporating non-financial factors such as societal and environmental parameters (Locatelli et al, 2014).

The selection criteria for a design characteristic may be based on an understanding of the implications on the lifecycle cost (Locatelli & Mancini, 2012a). Although alternative methods have been suggested for comparing NPP costs (see for example Linares et al, 2013; Roques et al., 2006; Rothwell, 2006) the Levelized Cost of Electricity (LCOE) is the most widely used metric for lifecycle cost analysis. The LCOE defines the "break even" cost for a power generation project at a specified rate of return (Palacios et al, 2004). LCOE analysis is used as a comparative benchmark between different power generation technology options (Locatelli & Mancini, 2012b) to support the rationale for energy policy and for investment decisions made by utilities (See for example (Gross et al, 2010); (Kessides, 2010); (Kula, 2015)).

LCOE has also been employed to provide a high-level comparison of the cost drivers for different generating technologies (Mari, 2004). The capital cost is the single largest contributor to the LCOE of a NPP (Maronati et al, 2018). In the LCOE analysis, however, other cost factors which may not have a representative importance based on cost driver analysis could be important for the commercial success of a future design. For example, fuel costs account for only 5% to 15% of the LCOE but could be an important decision driver in the future energy mix, particularly in a scenario where uranium prices increase, and alternative fuel types are considered (Baschwitz et al, 2017).

The successful investment and commercialisation of SMRs is dependent on multiple stakeholders across the lifecycle of a NPP (Locatelli & Mancini, 2011). There is a positive correlation between formal requirements capture techniques and the degree of success in complex engineering projects (Söderholm et al, 2014). An improved understanding of customer needs generally leads to the successful deployment of new products, sometimes in a shorter development time (Kahraman et al, 2006). The estimates generated at the design stage often employ scaling factors from large NPPs (Cooper, 2014). However, the economic drivers for SMR technology are fundamentally different to LRs. LRs have a larger upfront cost which is balanced against economies of scale which are achieved through a large electricity generation capacity. Conversely, SMR costs may differ significantly, where economies of multiples are used to reduce the upfront cost of capital, sacrificing the electrical capacity. In cases where future technologies are not expected to follow historical trends, or in situations where there is a lack of available historic data, expert elicitation is identified as a method of obtaining an understanding of the sources of cost and their uncertainties (Levi & Pollit, 2015).

The method, presented in Section 2, describes a novel approach to using expert elicitation to understand the relative importance of cost factors influencing the LCOE. The objective of this study is to identify and analyze the requirements of cost information for key stakeholders associated with various stages of the lifecycle of the SMR. Section 3 describes the stakeholder analysis used to identify key influencers on the successful commercial deployment of the SMR. The stakeholder analysis is considered for different stages of the product lifecycle. Cost experts representing each of the key stakeholders rank the relative importance of each cost factor influencing the LCOE using a pairwise questionnaire. The results of the pairwise comparisons are analyzed using the Analytical Hierarchy Process (AHP). In Section 4 the cost factors which influence the LCOE are categorized for the pairwise comparison. The results of the AHP representing the relative importance of cost factors from the perspective of each individual stakeholder are presented in Section 5. Key findings from the AHP analysis and the implications of the results on understanding of cost factors are reviewed in Section 6.

2 Method

A combination of stakeholder analysis and expert elicitation was used to rank the cost factors which form the inputs to the LCOE. Section 2.1 describes the stakeholder analysis approach used. Section 2.2 presents a short overview of the AHP technique and how it was employed in this study.

2.1 Stakeholder Analysis

Stakeholder analysis is the systematic “identification of stakeholder groups, their interest levels and ability to influence the project or programme” (APM, 2006). The needs of different stakeholders are often identified as being incongruent, with multiple strategies needed to manage stakeholder expectations associated with project outcomes (Lin et al, 2017). Using structured interviews Doloi (2011) has shown that understanding stakeholder perspectives on project cost influencing factors can identify critical cost performance activities during a development programme. The key factors are different for each stakeholder ranging from political and economic to technical and attitudinal. An understanding of the cost information required by key stakeholders throughout the lifecycle can support the successful execution of a project.

Stakeholder analysis combined with Multi Criteria Decision Analysis (MCDA) provides a method for explicitly comparing the different objectives of key influencers (Marltunen et al, 2017). Read et al (2017) use MCDA engaging stakeholders to understand the importance for each aspect supporting the selection of an energy project. The criteria are divided into environmental, economic and socio-political criteria. Smyth et al (2018) identified the stakeholders for the Hinkley Point C construction project from the perspective of the UK Government. The key stakeholders identified as having the greatest impact and input on decisions before construction as the Government (British Government), the sponsor and owner of the plant (Electricité de France (EdF)), the financing organizations (EdF and China General Nuclear Power Company (CGN)) and the utility company (also EdF). Additional stakeholders were identified as having less influence on decisions prior to construction start including the end user of electricity, project enablers (Contractors and supply chain) and external stakeholders (Electricity consumers).

In this study stakeholder analysis was carried out from the perspective of a nuclear design vendor at the early design development stage for a SMR. A key stakeholder is defined in this study as one who is highly interested in the cost of the SMR and has the power to influence its successful deployment. Given the lengthy lifecycle of the SMR key stakeholders are likely to change for each phase (Aaltonen et al, 2008). This study incorporates the perspective of stakeholders from each defined lifecycle stage of the SMR.

The basic process for stakeholder analysis involves identifying the stakeholders, assessing the influence and interest levels, and proposing a prioritisation or ranking of stakeholders. Firstly, a list of all stakeholders was compiled (for brevity only the key stakeholders are identified in this paper). Stakeholder analysis was carried out for each lifecycle phase of the SMR. The product lifecycle can be defined as “the overall duration of a provider’s involvement over the product” (Settani et al, 2014). Figure 1 presents 7 different stages of the NPP lifecycle according to the Economic Modelling Working Group of the Generation IV International Forum (EWMG, 2007). The lifecycle of the SMR in this study is divided into the Design and Development, Construction and Operations stages.

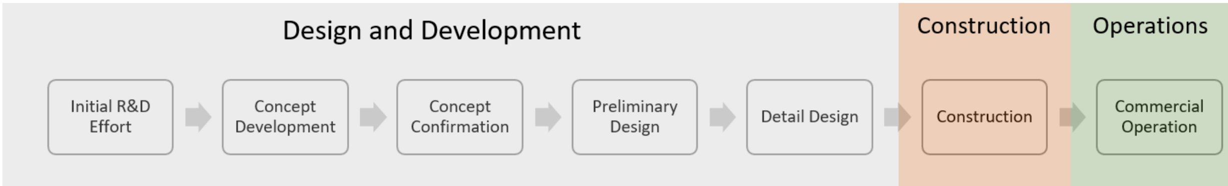

Figure 1: Stages of product lifecycle where cost estimates are generated according to recommended guidelines (adapted from EMWG (2007))

The “importance” of each stakeholder was assessed by the design team of the SMR against the control question “how important is ‘stakeholder x’ in determining the successful deployment of the SMR?” Importance was described in terms of the level of influence and interest of the stakeholder regarding the SMR. The “Influence” describes the ability for a stakeholder to make decisions which can affect the successful deployment of the SMR. The “Interest” is defined as the level of involvement a stakeholder has in the project at each lifecycle phase. The stakeholders were then assessed to understand the interest level to the SMR using a number ranking system. The judgements of the design team were then used to allocate the position of each stakeholder on an influence versus interest grid. A list of key stakeholders in each lifecycle phase was then used to identify the appropriate participants for the pairwise comparison stage.

2.2 Analytical Hierarchy Process

The Analytical Hierarchical Process (AHP) is a well-known MCDA method for assigning and ranking different, intangible but relational criteria (Saaty, 2001). An advantage of AHP is that the expert providing information does not need to produce a numerical response. AHP allows the decision-maker to directly compare qualitative and quantitative information through scaling which is particularly useful at the early design phase of a project, when non-functional requirements may be more descriptive and based on subjective responses.

Several studies have used AHP for ranking and decision weightings, applying these to the nuclear and power generation field. Aras et al (2004) used a combination of AHP and cost benefit analysis to determine the relative importance of different characteristics influencing the siting of power generation technology. Li et al (2016) used AHP as a decision support tool to prioritise tasks related to radiation protection precautions. Expert assessment is used for the importance ranking of various dimensions related to community resilience for disaster situations (Alshehri et al, 2015). where AHP is then employed to weight and rank each criterion. Even with a limited number of participants the AHP method provides a useful way of categorizing and achieving consistency in subjective responses. AHP has been applied to achieve consensus where there are conflicting, or subjective criteria (Franek & Kresta, 2014). Luzon & El-Sayegh (2016) assessed 10 key criteria for the selection of material suppliers for oil and gas projects using AHP combined with expert elicitation from 8 participants with expertise on major projects.

The purpose of applying AHP in this study was to determine the importance ranking of cost factors which are likely to impact the commercial success of a near-term deployable SMR. The rankings are dependent on the relative importance placed on the presented options. The AHP method was implemented in four steps (Figure 2). Franek & Kresta (2014) present a shortened explanation which clarifies the key points of carrying out an AHP analysis. For a complete explanation on the assigning and assessment of pairwise comparisons using AHP see Saaty (1987).

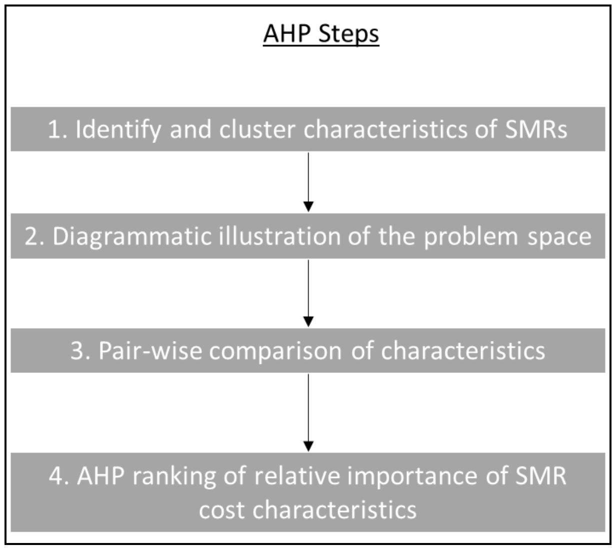

Figure 2: AHP approach used in study (adapted from Franek & Kresta, 2014)

The first step was to identify the cost factors and to cluster them into representative groups with a common theme. A review of literature was used to identify the cost factors of the LCOE, which focused on peer-reviewed journals but also including internet-based sources such as government reports.

Step 2 involved producing a diagrammatic representation of the relationships in the AHP hierarchy. Expert elicitation was then used to generate a pairwise comparison of each of the identified cost factors in terms of the goal using a questionnaire. The identified participants were approached through directed email invitations to complete a questionnaire survey. The goal of the pair-wise comparison was clearly outlined on the questionnaire form and the experts confirmed their understanding that they were expected to use their judgement to rank each pair of characteristics in turn.

Qualitative responses from the questionnaire were translated using Saaty's preference scales applying ratings from 1 to 9 for each comparison (Table 1). Other scaling methods have been produced however the linear scaling applied by Saaty is generally used as the reference standard method (Lanjewar et al, 2016).

Table 1: AHP pairwise comparison scale used for questionnaires (adapted from Saaty (2001)

Quantitative Representation	Description of relative importance used in pairwise comparison
1	Equal importance

3	Moderate importance
5	Strong importance
7	Very strong importance
9	Absolute importance

The numeric paired comparison values obtained from the participants for *n* characteristics were tabulated in a positive reciprocal matrix. S_{ij} represents the relative importance of characteristic *i* with respect to characteristic *j*. S=(S_{ij}) for each assigned value in the matrix of the *i*th characteristic with respect to the *j*th, the opposite characteristic (where the *j*th is presented with respect to the *i*th) becomes the reciprocal value, S_{ji} = 1/ S_{ij}. In the matrix, S_{ij} = 1 when i = j, so that a characteristic compared with itself is always assigned a value 1. All the diagonal entries of the pairwise comparison matrix, therefore, are equal to 1.

$$\mathbf{S} = \begin{pmatrix} 1 & s_{12} & \dots & s_{1n} \\ 1/s_{12} & 1 & \dots & s_{2n} \\ \dots & \dots & \dots & \dots \\ 1/s_{1n} & 1/s_{2n} & \dots & 1 \end{pmatrix}.$$

The results were then normalised and the highest eigenvalue for the matrix, λ_{max} was determined. As the matrix eigenvector approaches the number of characteristics, the consistency of the matrix improves (Lanjewar et al, 2016). Each element was checked to determine if they were linear independent using a consistency ratio (CR). For a given number of elements, the Consistency Index (CI) is calculated:

$$CI = \frac{\lambda_{\max} - m}{m - 1}$$

A set of Random Consistency Index (RI) developed by Saaty (1987) is then used to produce the CR for the matrix:

$$CR = \frac{CI}{RI}$$

The larger the number of pair-wise comparisons made the increased likelihood there is of a consistency error being introduced. The CR illustrates the deviation from consistency, so that a smaller value of CR indicates lesser deviation from consistency. A perfectly consistent matrix will have a CR=0. A CR of less than 0.1 is reasonable, where anything higher than 0.2 should be re-evaluated (Shin et al, 2016).

3 Identifying and Ranking Key Stakeholders

The overall results of the stakeholder analysis carried out within the vendor organisation is presented in Appendix A. During the listing stage 31 stakeholders were identified as having some interest or influence on the commercial success of the SMR. Five important stakeholders who are key to the successful commercial deployment of the SMR were identified by the design team. The scope of the analysis presented in this paper is limited to the stakeholders identified in Table 2. The dynamic analysis shows how the importance and interest changes over the product lifecycle of the SMR.

Table 2: Summary rank of stakeholder importance at different stages of the SMR product lifecycle

Rank Importance	Start (R&D Phase)	Design Acceptance	Construction Phase	Operations Phase
1	Reactor Vendor	Reactor Vendor	Utility/owner operator	Utility/owner operator
2	Funding Agency	Funding Agency	Funding Agency	Funding Agency
3	Policy Makers	Utility/owner operator	Construction Firm	Policy Makers
4	Utility/owner operator	Policy Makers	Reactor Vendor	Reactor Vendor
5	Construction Firm	Construction Firm	Policy Makers	Construction Firm

The Reactor Vendor plays a key role across the early stages of the product lifecycle, particularly across the design phase. When the concept design is confirmed the ability to move on to the next stage of design is dependent on further investment. Further investment may come from a Government funding agency, as well as investment from within the reactor design organization itself or a private utility.

At the construction phase there are multiple key stakeholders of high importance who can influence the commercial success of the SMR. These consist of the Utility Owner, Funding Agency and the Construction Firm. The design team still influence the cost of the SMR during construction, particularly if late changes are required to the design.

During the operations phase the key stakeholders become focussed on the ongoing operational viability of the plant. The investors are interested in the return on investment, and the rate of capital repayments. The Utility becomes the key stakeholder for cost, to remain competitive in the electricity market.

The Policy Maker, although never observed to be the highest-ranking importance stakeholder, nevertheless plays a key role in supporting the deployment of the SMR through implementing policies which lead to the commercial success of the design. The Government is an important stakeholder during the development phase. Policy Makers are interested in how to facilitate the development or implementation of new technologies, but they also have a key role in influencing the continued economic competitiveness during the O&M stage.

The Owner/ Operator of the plant is responsible for a significant amount of the decisions to be made for the plant, including the lifecycle economics of the plant (IAEA, 2006). The Reactor Vendor is responsible for proving aspects of the performance of the plant, such as the simplification, constructability, operational reliability, and the project schedule capability. As these requirements are often linked to the economic feasibility of a NPP, the Vendor is identified as a key stakeholder. During the construction and O&M stage it is the owner/ operator who then becomes the key stakeholder. The analysis did not identify the nuclear regulator as a key stakeholder for cost. Changes in regulation have been identified as a cause of the cost escalation associated with constructing NPPs, particularly in the United States (Koomey & Hultman, 2007). In this analysis the regulator has a high influence on the successful commercial deployment of the SMR but is not identified as having a high interest in the cost.

4 Identifying LCOE Inputs

A review of literature is used to identify the cost factors which influence the LCOE. The literature search focused on peer reviewed journal articles and conference papers related to financial and economic nuclear cost estimating. As well as financial and economic related papers, the search also returned results related to the human and environmental cost of civil and defence nuclear applications. To concentrate on the most relevant material, the abstracts of each article were reviewed, with those papers that are not related to the financial or economic aspects of power generation filtered out.

4.1 Purpose of LCOE Analysis

Lifecycle cost calculating methods and assumptions vary depending on the intent of the study and therefore any such calculation requires a viewpoint (Settanni et al 2014). The LCOE estimate is generally presented within a specific environmental context such as the expected market structure, expected electricity demand growth, and the impact of environmental policy for example a carbon tax. The scope of an LCOE estimate can vary significantly depending on the purpose of the study (Table 3).

Table 3: Review of LCOE estimates and conclusions from studies

Author (year)	Type of Estimate	Purpose of estimate	Conclusions due to Estimate
IEA (2015)	LCOE	Policy Decision Support	Market structure, policy environment, resource availability drives the LCOE

MIT (2009)	LCOE	Policy Decision Support	Nuclear power can reduce risk-premium through proven performance. Carbon tax positively impacts on nuclear competitiveness
University of Chicago (2004)	Overnight Cost of Construction	Policy Decision Support	Nuclear power cost driven by financing options due to high capital cost contribution to LCOE. Availability of more detailed overnight construction cost information may impact future investment in new nuclear plants.
NREL (2012)	LCOE	Utility Investors	Small improvements to technology or manufacturing processes can lead to significant cost savings. Cost is site-specific. LCOE impacted by variation in required rate of return, O&M costs, and debt-financing structure
Mott MacDonald (2010)	LCOE	Policy Decision Support	Less mature technologies have a more extensive first of a kind premium. Cost uncertainty associated with fuel and carbon prices.
Lazard (2015)	LCOE	Policy Decision Support	Cost drivers for capital intensive technologies are engineering, procurement and construction cost, build time, and the annual capacity factor
DECC (2013)	LCOE	Policy Decision Support	Capital costs the biggest driver of nuclear LCOE
Allan et al (2011)	LCOE	Policy Decision Support	Cost reduction for newer technology achievable with technology-differentiated financial support
Gross et al (2010)	LCOE	Policy Decision Support	Policy makers need to maintain awareness of revenue risk as well as initial capital (cost) risk. Government

			support to fixed price for electricity where technology uncertainties are greater is right
Kennedy (2007)	LCOE	Policy Decision Support	Lower LCOE can be achieved when investing in multiple units rather than one off. Coupled with carbon tax nuclear would be competitive in the UK context
Carelli et al (2010)	LCOE (LUEC in the paper)	Utility investors	Carbon tax improves investment attractiveness of a small NPP.
Locatelli & Mancini (2012)	LCOE + non-econometric requirements	Utility Investors	Large reactors meet traditional metrics of IRR and LCOE better than SMRs. Other metrics associated with design robustness and spinning reserves better achieved by SMRs. Consideration required of all these factors when assessing suitability of technology.

LCOE estimates are used to identify the required level of financial support to encourage investment in a technology which might not be selected if left to the market (Gross et al, 2010). For example, the US Energy Policy Act of 2005 introduced loan guarantees, production tax credits and guarantees against some construction delays for the first 6GWe of new NPPs (MIT, 2009). From a government investment support perspective, the costs incurred can include the R&D requirements, and other early work.

Mari (2014) identified that the LCOE was an effective tool for Government to identify both the societal impact of power generation technology (e.g. carbon emissions and waste), and the sensitivity to market influences such as the risk factor associated with investment in a liberalized or regulated environment. Roth & Ambs (2004) attempted to produce a comparison of LCOE figures for different electricity generating technologies by incorporating externalities such as air quality and energy security into a full fuel cycle LCOE estimate. An additional benefit from the utility perspective is that the LCOE provides an understanding of the generating costs associated with the power generation technology.

Despite its widespread use as a measure for determining large energy investments there is no internationally recognised standard to determine the cost of nuclear power

(Kessides, 2010). Different methods are used to account for costs in different lifecycle phases leading to a lack of consistency in the LCOE analysis (see example Boccard (2014); Feretic & Tomsic (2005); Hall (2004); MIT (2003)). There appears to be no clear scope of what should be included in the LCOE. Darling et al (2011) identifies how LCOE values are generally stated with underlying assumptions not being explicitly stated. Despite both academic literature and industry refer to a LCOE figure, there is no consensus on its implementation or on the assumptions used to generate input values.

4.2 Elements of the LCOE

In its simplest form the LCOE is a ratio of lifetime costs over the expected net electricity generated for the operational life of the plant (Mott MacDonald, 2010). Lifecycle costs of NPPs can be categorized generally based on the review of LCOE literature as shown in Figure 3. A complete cost analysis of nuclear power includes capital, operating and decommissioning costs, as well as the cost of externalities (Leveque 2013). However, the LCOE figure does not always explicitly define the costs for each individual lifecycle phase. For example, the EIA (2016) identified the key aspects of the LCOE calculation for baseload technologies as the overnight capital, fuel, O&M, financing and utilisation rate, and noted but did not incorporate incentives such as carbon cost or tax credits. Decommissioning or waste management costs may or may not be incorporated into the capital or O&M inputs, though this is not always explicitly stated.

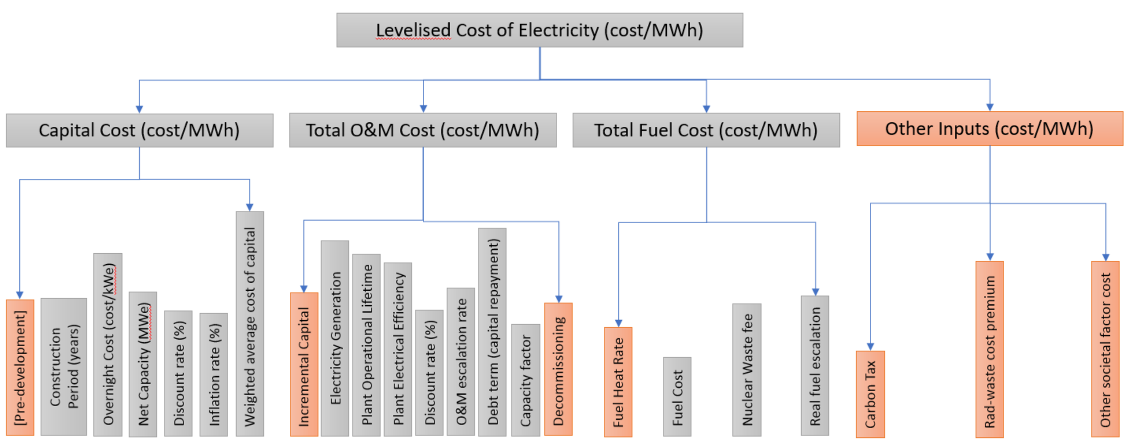

Figure 3: Standard LCOE inputs with additional categories for scenario analysis

The DTI (2007) define pre-construction costs as those associated with work carried out to secure planning and consent approval. The value of overnight construction costs (OCC) is important in understanding the direct cost of a build project. The OCC removes the influencing factor of cost of capital, allowing individual reactor designs to be assessed and considered separately from finance-related issues (Cantor & Hewlett 1988).

According to Thomas (2005), the cost of capital could range between 5% to 15%, depending on the competitiveness of the electricity market, the utility, the country risk and the credit rating of the company. The uncertainty range of the LCOE of a NPP is driven by the selected cost of capital value (Riesz et al, 2017). The interest during construction is added to the overnight construction cost to produce a figure for total capital cost. The interest accrued is dependent on the financing arrangements in place to pay for the construction of plant. Estimates of construction cost do not always include the cost of borrowing or the interest accrued during construction (Sovacool 2010).

Operations and maintenance (O&M) costs can be defined as those incurred after construction and are characterised as annual production costs (ORNL 2003). The University of Chicago (2004) study referred to 5 separate cost components associated with the operations phase, namely the annuitized capital cost, insurance, fixed O&M, variable O&M, and fuel costs. The DTI (2007) study defines O&M costs as those which "relate to the management and upkeep of a power station during its lifetime." With high utilization and the large scale of the NPP, the fixed O&M costs can be spread over the total electrical output (Thomas 2005). The capacity factor and operating life of the NPP have a direct influence over the generating revenue, and therefore the ability to provide a return on investment. LRs must operate at as close to their stated electrical output capacity as possible to payback on the upfront cost of construction (Leveque 2013).

Locatelli & Mancini (2010) provide a review of the costs associated with decommissioning, identifying that a common high-level structure can be used to cost a NPP decommissioning project. There is variability in how the allocation of funds for decommissioning is treated within the calculation of LCOE, with some studies treating it as a fixed O&M cost, while others treat it as a variable cost, related to the capacity of the plant. Decommissioning costs can be included or separated from nuclear waste disposal costs.

Externalities are scenario and case specific, so it could be reasonable to consider the influence of these factors are being considered in the LCOE estimate. A number of academic studies either focused on, or considered as an input, the cost of carbon. Heck et al (2016) calculated the amortized carbon cost across the operations life of a generating plant. MIT (2003) presented scenarios which also included an assumed carbon tax on the electricity generated, raising the cost of comparative fossil fuel plants. Kennedy (2007) specifically considered a carbon tax for the cost and benefit analysis of different new energy generation technology for new build in the UK. De jong et al (2015) focused on the externalities associated with environmental and social impacts of the power generation technologies in the context of Brazil's electricity mix.

4.3 Sensitivities and Driving Factors

The capital cost for a LR is the biggest proportion of the overall lifecycle cost of the plant. The time associated with pre-construction and construction activities are dependent on the technology, construction experience, and site-specific costs (DECC 2013). Construction time has a major influence on the cost of capital and therefore on the overall LCOE figure. Estimated construction duration will also impact the cost of construction, as will the influence of construction delays. Harris et al (2013) included an annual construction escalation cost of 5.4% to illustrate the impact of construction delays on the LCOE. The LCOE calculation produced by Linares (2013) does not reflect the impact of inflation, explaining that all technologies considered will be impacted by inflation in a similar way.

The cost of capital can be a dominating input for the construction cost, potentially inhibiting the comparison of other important input factors, such as the direct construction cost of the reactor design itself. The sensitivity of the LCOE to changes in the cost of capital is commonly applied (Mari, 2014), and the level of risk can have a major influence on the final analysis for technology selection. Providing assumptions on the debt profile can help to show policy makers how different mechanisms can assist private investment (MIT, 2003). The cost of capital is subject to the discount rate used and the baseline year used to determine the start of the O&M stage (Leveque 2013).

O&M costs are significant to the investment decision, as well as to understanding the market mechanisms required for new build economics in the future (MacKerron, 1992). Hewlett (1992) estimated that around 10% of NPPs would not be competitive in the US market and would be forced to retire before the 40-year licensed life because of the poor operating capacity factor experienced to date. The uncertainty around future operating costs was a major factor in the decision to close several US NPPs during the 1980s (Stucker 1984). The low cost of competitive fossil fuels currently being experienced is causing some utilities in liberalized markets to reconsider new nuclear power investment and to close operating plants (World Nuclear News 2016). Fuel cost is influenced by the cost of uranium and the cost of fabricating the fuel assemblies (Pannier & Skoda 2014). Additional costs may be incurred if utilizing a twice-through cycle such as MOX fuel (De Roo & Parsons 2011). On the other hand, Kessides (2010) argues that nuclear operations costs are insensitive to fossil fuel prices.

It is still expected that the cost of decommissioning will be discounted across the operating life of the plant and treated as a fixed cost within the O&M phase. Despite the relative insignificance of the cost of decommission in the LCOE calculation, it is still a factor that needs to be included, primarily as a link to extrinsic influences such as the perceived societal impact of waste.

4.4 LCOE Inputs for AHP Analysis

Of interest in this study is the extent to which different stakeholders consider the relative importance of cost influencing factors on the commercial success of a near-term deployable SMR. The costs are categorized based on the areas which could be influenced intrinsically by the design development of the plant, and those extrinsic factors which are influenced by nuclear policy or the environment in which the SMR is built and operated. The main elements developed for the AHP analysis are identified in Table 4.

Table 4: LCOE influencing cost factors categorised for the AHP analysis

Cost Reference	Cost Element	Description
C1	Direct Costs	Overnight Cost of construction and O&M costs directly attributed to the reactor design
C2	Construction Schedule	The time taken to construct the plant from the start of pre-construction activities to the point where the plant begins to supply power to the grid
C3	Plant Availability	The amount of time the reactor is operating, therefore generating power. This represents the revenue stream for the plant
C4	Project Financing	The source of finance which influences the cost of capital and reflects the risk associated with the investment
C5	Externalities	The impact of social and environmental costs (e.g. the cost of carbon) associated with nuclear power

Direct costs are to a large extent within the control of the Vendor (Kidd, 2013). The direct costs (C1) are influenced primarily by the design of the plant. The vendor can influence the direct construction costs, O&M cost, and the fuel required through functional requirements definition at the early design stage. The construction schedule (C2) and plant availability (C3) are also influenced by the design of the plant but may also be significantly influenced by extrinsic factors. For example, the specified design may have a planned construction schedule, but is potentially influenced by common construction delays related to labour productivity, procurement problems and regulatory changes. Similarly, the plant may have a reference design capacity which could be influenced by the utility operating environment, market conditions (such as the fluctuating gas prices in a merchant-style energy market) or regulatory changes.

Project financing (C4) and Externalities (C5) are primarily influenced by policy makers and market forces. The lower capital cost can result in a perceived reduction in investment risk (Linares & Conchado, 2013). For a private utility investor this could be a significant advantage (Locatelli & Mancini, 2011). The inclusion of externalities may be more relevant to policy makers and government than for private investors (Vazquez 2016).The cost of capital will be determined by the source of financing used to construct the plant, while environmental policies such as a cost for carbon will be a driver of external costs associated with the power plant.

5 AHP Study

5.1 Defining the Problem Space

Each of the cost factors identified in Section 4.4 is formed into clusters representing the AHP elements in the analysis (Figure 4). The “control” question is treated as a source term, i.e. it has influence on the factors considered which influence cost, but these factors do not influence the control. The sub-factors describe the categories which have been identified as inputs to the LCOE analysis method.

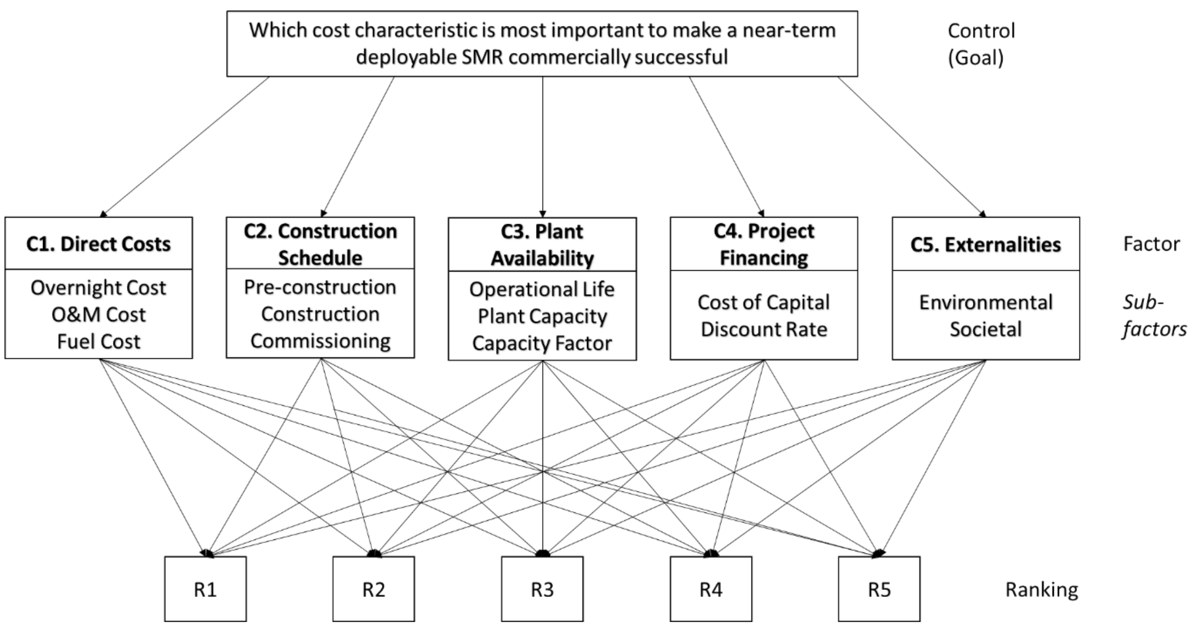

Figure 4: Hierarchical definition of the cost elements influencing the commercial success of the SMR

5.2 Pairwise Comparison

Table 5 lists the participants in the pairwise comparison study. Each participant is

Government for between 5 and 10 years. Each participant represents the perspective of each of the key stakeholders identified in Section 3. The significant experience in nuclear cost estimating and experience-based understanding of the influences on the cost of NPPs is a distinct advantage in this study.

Table 5: List of expert participants to elicitation study

Stakeholder Represented	Title	Years of experience
Funding agency	Head of financial analysis (Government Institution)	5-10 years
Reactor design	Reactor Design Senior Manager	11-20 years
Policy maker	Energy Data Analyst	5-10 years
Construction firm	Head of Nuclear Construction Engineering Company	11-20 years
Utility owner/ operator	President of nuclear utility	11-20 years

A questionnaire for the pair-wise comparison of cost factors identified in Section 4.2 was completed by each participant. Each pair of cost factors is compared against the statement "which of the two cost requirements of the SMR is more important in making a near-term deployable SMR commercially successful?" The results of the pair-wise comparison (Table 6) are used to conduct the AHP analysis.

Table 6: Pairwise Comparison Results from Each Stakeholder

Funding Agency

Criteria	C1	C2	C3	C4	C5
C1	1	1	9	1/3	5
C2	1	1	7	1	7
C3	1/9	1/7	1	1/5	1/3
C4	3	1	5	1	5
C5	1/5	1/7	3	1/5	1

Reactor Design

Criteria	C1	C2	C3	C4	C5
C1	1	5	3	1	1
C2	1/5	1	1/3	1/7	1/5
C3	1/3	3	1	1/3	1
C4	1	7	3	1	5
C5	1	5	1	1/5	1

Policy Maker

Criteria	C1	C2	C3	C4	C5
C1	1	1	5	1	7
C2	1	1	9	1	9
C3	1/5	1/9	1	1/9	1/5
C4	1	1	9	1	5
C5	1/7	1/9	5	1/5	1

Construction Firm

Criteria	C1	C2	C3	C4	C5
C1	1	1	5	1/7	3
C2	1	1	3	1/5	7
C3	1/5	1/3	1	1/9	1
C4	7	5	9	1	9
C5	1/3	1/7	1	1/9	1

Utility Owner/ Operator

Criteria	C1	C2	C3	C4	C5
C1	1	1	7	1/3	3
C2	1	1	9	1/3	3
C3	1/7	1/9	1	1/7	1/5
C4	3	3	7	1	9
C5	1/3	1/3	5	1/9	1

5.3 AHP Results

Row Geometric Mean Method (RGMM) is applied to normalise the weightings, applying rankings based on the importance of each pair-wise comparison. Normalized values for the pairwise comparisons are produced for each stakeholder (Table 7). The highest eigenvalue for the matrix, λ_{max}, consistency index (CI), and Consistency ratio (CR) are presented in Table 8. A Randomness Index (RI) value of 1.12 is applied in the calculation of the consistency. Results obtained from the initial pairwise comparison were outside of the acceptable consistency range of 0.2. The participants were requested to re-evaluate the pairwise comparisons. The results of the follow up pairwise comparison are found to be within the acceptable consistency range and are presented in this paper.

Table 7: Normalised results for pairwise comparison

Funding Agency

Criteria	Direct Costs	Construction Schedule	Plant Availability	Project Financing	Externalities
C1	0.188284519	0.304347826	0.360000000	0.121195122	0.272727273
C2	0.188284519	0.304347826	0.280000000	0.265853659	0.381818182
C3	0.020920502	0.043478261	0.040000000	0.073170732	0.018181818
C4	0.564853556	0.304347826	0.200000000	0.365853659	0.272727273
C5	0.037656904	0.043478261	0.120000000	0.073170732	0.054545455

Reactor Design

Criteria	Direct Costs	Construction Schedule	Plant Availability	Project Financing	Externalities
C1	0.283018868	0.217391304	0.360000000	0.378151251	0.121951220
C2	0.056603774	0.043478261	0.040000000	0.042016807	0.024390244
C3	0.094339623	0.130434783	0.120000000	0.126050420	0.121951220
C4	0.283018868	0.391304348	0.360000000	0.378151261	0.609756098
C5	0.283018868	0.217391304	0.120000000	0.075630252	0.121951220

Policy Maker

Criteria	Direct Costs	Construction Schedule	Plant Availability	Project Financing	Externalities
C1	0.299145299	0.310344828	0.172413793	0.302013423	0.315315315
C2	0.299145299	0.310344828	0.310344828	0.302013423	0.405405405
C3	0.059829060	0.034482759	0.034482759	0.033557047	0.009009009
C4	0.299145299	0.310344828	0.310344828	0.302013423	0.225225225
C5	0.042735043	0.034482759	0.172413793	0.060402685	0.045045045

Construction Firm

Criteria	Direct Costs	Construction Schedule	Plant Availability	Project Financing	Externalities
C1	0.104895105	0.133757962	0.263167895	0.091277890	0.142857143
C2	0.104895105	0.133757962	0.157894737	0.127789047	0.333333333
C3	0.020979021	0.004458599	0.052631579	0.070993915	0.047619048
C4	0.734265734	0.668789809	0.473684211	0.638945233	0.428571429
C5	0.034965035	0.019108280	0.052631579	0.070993915	0.047719048

Utility Owner/ Operator					
Criteria	Direct Costs	Construction Schedule	Plant Availability	Project Financing	Externalities
C1	0.182608696	0.183673469	0.241379310	0.173553719	0.185185185
C2	0.182608696	0.183673469	0.310344828	0.173553719	0.185185185
C3	0.026086957	0.020408163	0.034482759	0.074380165	0.012345679
C4	0.547826087	0.551020408	0.241379310	0.520661157	0.555555556
C5	0.060869565	0.061224490	0.172413793	0.057851240	0.061728395

Table 8: Consistency check for AHP matrices

Participant	λ_{max}	Consistency Ratio	Consistency Index
Funding Agency	5.442110841	0.098685456	0.11
Reactor Design	5.310280384	0.06925901	0.08
Policy Maker	5.512889804	0.114484331	0.13
Construction Firm	5.453435107	0.101213193	0.11
Utility owner/ operator	5.428382745	0.095621148	0.10

The outcome from the AHP analysis is a set of importance rankings for each of the cost factors used in the LCOE analysis from the perspective of each stakeholder (Table 9). Each stakeholder had a clear top rank, and a clear lowest ranked priority. Three of the five stakeholders (Reactor Design, Construction Firm and the Utility Owner/ Operator) ranked project financing as the highest importance cost factor influencing the commercial success of a near-term deployable SMR. From the Funding Agency perspective, the most important factor is the direct costs associated with the design itself, while from the Policy Maker perspective the construction schedule is identified as the highest priority.

Table 9: AHP ranking of importance of each cost element for each stakeholder

Cost Factor	Funding Agency	Reactor Design	Policy Maker	Construction Firm	Utility owner/ operator
Direct Costs	**37.40%**	27.50%	28%	14.70%	19.30%
Construction Schedule	30.60%	4.40%	**32.50%**	17.20%	20.70%
Plant Availability	3.60%	12.10%	3.40%	4.70%	3.40%
Project Financing	21.80%	**39.20%**	28.90%	**58.90%**	**48.30%**
Externalities	6.60%	16.80%	7.10%	4.50%	8.30%

6 Discussion

At a high level, considering all criteria and all stakeholder opinions project financing is expected to be the most important cost factor influencing the commercial success of a near-term SMR (Figure 5). All stakeholders ranked externalities and plant availability as the lowest or near to the lowest importance relative to the other cost factors. While there is general consensus not all stakeholders agree as to what the top influencing cost factor should be. The Construction Firm and Utility Owner/ Operator have similar opinions on the relative importance of each of the cost factors, identifying project financing as of key importance to the commercial success of the plant. The Funding Agency and the Policy Maker also hold similar views to each other, prioritising direct costs and construction schedule, although the Policy Maker places a higher priority on the project financing. The Reactor Vendor places a high priority on the project financing, in line with the priority ranking of the Construction Firm and the Utility/ Owner Operator, while also placing a high importance on direct costs, in line with the priority of the Funding Agency.

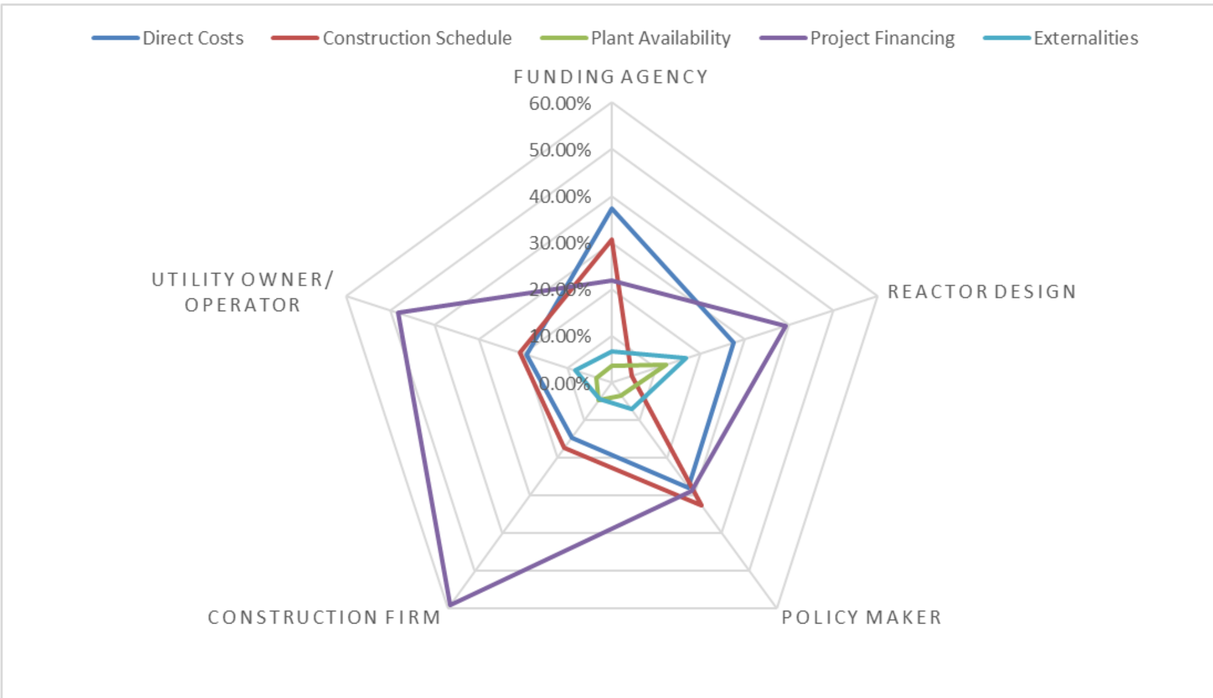

Figure 5: Comparison of weighted cost requirements

6.1 Conflicting stakeholder cost requirements

The stakeholder analysis has been carried out from the perspective of the design vendor at the early concept design phase of the SMR. A key assumption in this paper is the need for a design vendor to understand the requirements of cost from the perspective of key stakeholders. The discussion, therefore, focuses on the relative importance placed on each of the considered criteria between the design vendor and each of the key stakeholders.

In the stakeholder analysis the Reactor Designer and Utility Owner/ Operator are ranked as the most important stakeholders throughout the product lifecycle (See Table 2). Figure 6 shows a direct comparison of the cost factor ranks identified from the two perspectives. From both the Reactor Designer and Utility Owner/ Operator perspectives project financing appears to be the most important factor while direct costs second highest. There appears to be some consistency between the rankings provided by each of the key stakeholders, suggesting that there is similarity in understanding of the importance of different cost driving factors.

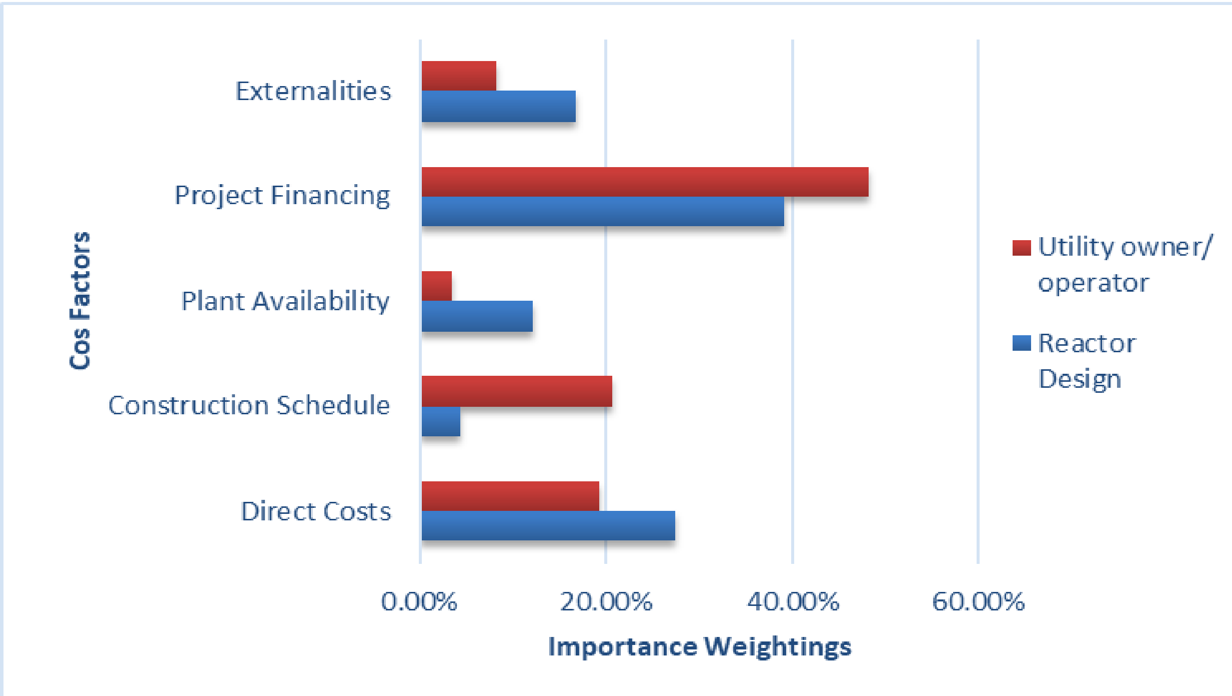

Figure 6: Comparison of Cost Factor Importance Weights between reactor design and utility owner/ operator

When the concept design is confirmed the ability to move to the detailed design stage is dependent on further investment. Further investment may come from a Government funding agency, or investment from the reactor vendor itself. The increase in product maturity through achieving design acceptance could reduce the perceived risk around the SMR, potentially reducing the cost of finance which the investor is willing to provide.

During the operations phase the key stakeholders become focussed on the ongoing operational viability of the plant. The investors are interested in the return on investment, and the rate of capital repayments. Several stakeholders with an indirect, but potentially significant, influence on the operational competitiveness are omitted in this analysis. For example, consideration could be given to the electricity grid stakeholder, a key influence on the system cost of the electricity generated. In some markets, such as the UK, it is expected that policy mechanisms such as Contracts for Difference (CfD) and agreed spot prices would largely regulate the cost of generated electricity.

The stakeholder analysis presented in Table 2 also identified that the Funding Agency was consistently important, and so their cost priorities are also compared with the Reactor Design stakeholder (Figure 7). The Funding Agency places a much greater level of importance on direct costs. A low priority is placed on the plant availability from the Funding Agency stakeholder. Plant availability is directly related to the revenue generation, and therefore, payback on investment associated with the project.

Although there is some agreement that direct costs associated with the design and the construction schedule are also important cost factors, there is little agreement on the importance weightings. It can be argued that each of the identified cost factors have some level of interdependency. By reducing the OCC, direct O&M, and construction schedule for the SMR, the cost of capital can be expected to reduce. The cost of capital is linked to interest during construction and is a direct measure of the impact of construction schedule and the associated delays. Plant availability is also linked to other cost requirements. For the reactor designer plant availability is a direct result of meeting key functional requirements such as planned plant efficiency. For the utility it is linked to the operational strategy.

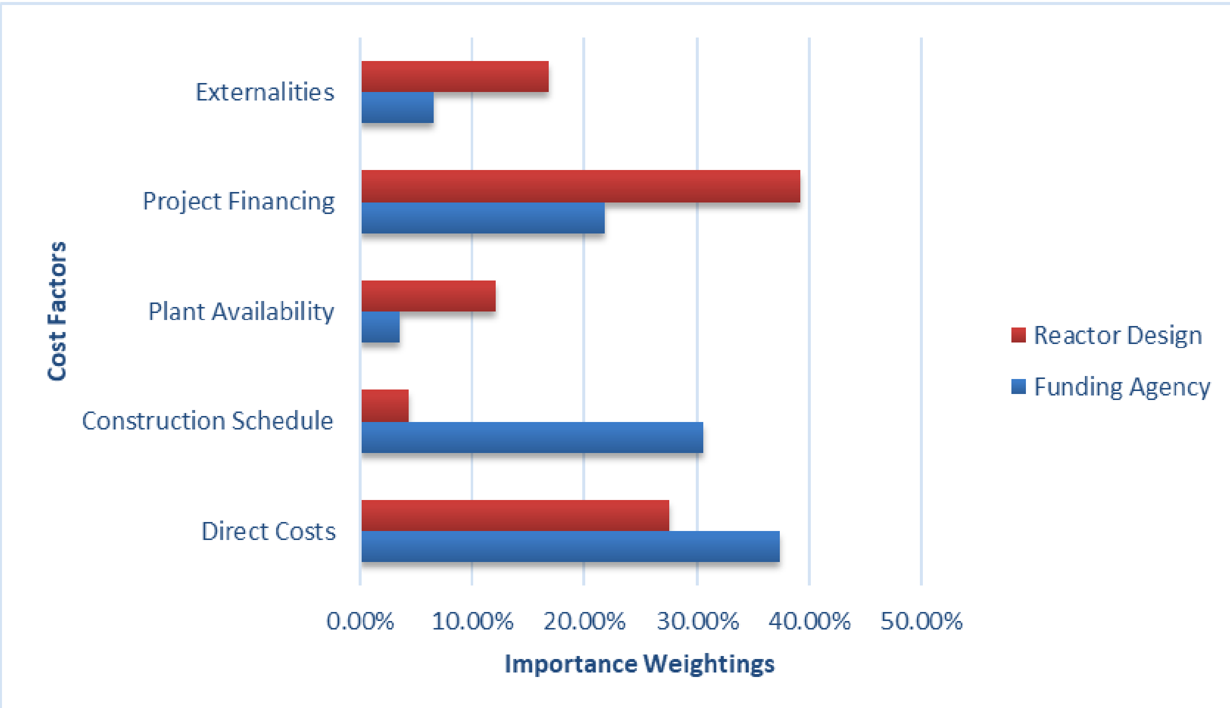

Figure 7: Comparison of Cost Factor Importance Weights between Reactor design and funding agency

The number and type of stakeholder considered in this paper are considered from the perspective of vendor in the UK market. A more vertically integrated NPP operator in a different market may reduce the number of stakeholders that would need to be considered, providing a clearer focus on the requirements of the owner/ operator of the plant. Whereas a nation embarking on nuclear power for the first time will require the designer to consider more perspectives, such as the national infrastructure requirements for the development of a nuclear program.

6.2 AHP Rankings

The AHP method has provided a clear ranking of different cost elements from the perspective of the stakeholders, illustrating the importance of different cost factors to each stakeholder. AHP was conducted with stakeholders presenting a snapshot through different lenses associated with each lifecycle phase of a NPP. The method applied in this study does not weight the importance of each stakeholder at each lifecycle phase.

Nor does it go as far as determining which SMR designs meet the criteria associated with each expert's ranking. This can be achieved through re-normalising based on weighted importance of each stakeholder as a customer of the reactor designer. Depending on the project lifecycle phase, the target customer, and other environmental factors, the power and weight associated with each stakeholder is likely to change.

The main limitation of this study is that the AHP method assumes the relationships between various interacting levels is uni-directional, that is, the dependency links are hierarchical with no feedback between the identified nodes (Meade & Presley, 2002). The criteria for pair-wise comparison must not be linked to the characteristics. This analysis is limited in its consideration of the interrelationships between each element within a cluster. For interrelationships between different elements within each cluster Analytical Network Process (ANP) could be employed. The main drawback to employing ANP is the large effort required to account for a larger number of interrelated relationships using pairwise comparisons. However, at least 5 interrelating elements exist for each of the 5 high-level characteristics clusters used in this study. An ANP analysis of these elements would require the number of comparisons to be 50*(50-1)/2 = 1225 pairwise comparisons. This may be unfeasible in practice for expert judgement and could increase the likelihood of a consistency error being introduced.

7 Conclusions

Accounting for the importance of different cost factors which can influence stakeholder satisfaction is critical to the commercial success of the SMR. The main contribution of this paper is a method to rank the importance of different cost factors on the commercial success of the SMR from the perspective of key stakeholder.

The AHP method can assist the vendor with ranking the importance of each cost factor from the perspective of different stakeholders when making design decisions. This may be particularly useful where the design team must consider multiple, possibly conflicting requirements. When comparing the cost impact of alternative options the weightings can be used to understand the impact of policy strategy or an investment decision.

The extent to which access is available to cost experts will determine whether the approach taken in this paper is feasible. Further work can be done to elicit rankings from a wider number of experts, to obtain consistency on the ranked importance of each cost element.

SMRs have been described as more flexible in future applications, compared to LRs. SMRs are designed primarily for electricity production, however, the additional benefits of co-generation such as district heating in extreme temperature climates, and desalination processes for water supply to coastal regions, or process heat for industries could also be incorporated. Flexibility can also mean through matching grid demand, such that remote regions with small demand or limited energy options can be supplied with nuclear electricity, or the ability to support flexible investment for large scale power stations by providing several modules in series. Further studies could discuss the trade off for all size of reactors or could include the co-generation applications of AMRs.

8 Acknowledgements

The authors wish to acknowledge the expert participants involved in the study for their contribution to this paper. The authors also acknowledge gratefully the feedback provided by Dr Giorgio Locatelli of the University of Leeds and Paul Campbell of Rolls-Royce Plc. Finally, the authors would like to thank the detailed feedback from the reviewers, which has greatly improved this paper.

9 Funding

This work was funded by the Engineering and Physical Sciences Research Council Award, the Manufacturing Technology and Engineering Doctoral Centre and Rolls-Royce Plc [grant number 1533156].

10 References

Aaltonen, K., Jaakko, K., Tuomas, O. (2008). Stakeholder salience in global projects. International Journal of Project Management Volume 26, Issue 5, Pages 509-516. doi.org/10.1016/j.ijproman.2008.05.004

Allan et al (2011) Allan, G., Gilmartin, M., McGregor, P., Swales K. (2011). Levelised costs of Wave and Tidal energy in the UK: Cost competitiveness and the importance of “banded” Renewables Obligation Certificates Energy Policy Volume 39, Issue 1, Pages 23-39

Alshehri, S. A., Rezgui, Y., & Li, H. (2015). Disaster community resilience assessment method: a consensus-based Delphi and AHP approach. Natural Hazards, 78(1), 395–416. doi.org/10.1007/s11069-015-1719-5

APM. (2006) APM Body of Knowledge. Association for Project Management. Fifth Edition Page. Buckinghamshire. Page-159. ISBN-1-903494-13-3

Aras, A., Erdoğmuş, S., Koç, E. (2004). Multi-criteria selection for a wind observation station location using analytic hierarchy process. Renewable Energy, 29(8), 13831392. doi.org/10.1016/j.renene.2003.12.020

Baschwitz, A., Mathonnière, G., Gabriel, S., de Lavergne, JGD., & Pincé, Y. (2017). When would fast reactors become competitive with light water reactors? Methodology and key parameters. Progress in Nuclear Energy, 100, 103-113. doi.org/10.1016/j.pnucene.2017.05.028

Beis. (2018a). Advanced Nuclear Technologies: Policy Paper. London. Retrieved from https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies

Beis. (2018b). Nuclear Sector Deal: Policy Paper. London. Retrieved from https://www.gov.uk/government/publications/nuclear-sector-deal/nuclear-sector-deal

Boarin, Sara, et al. "Financial case studies on small-and medium-size modular reactors." Nuclear technology 178.2 (2012): 218-232.

Boccard, N. (2014). The cost of nuclear electricity: France after Fukushima. Energy Policy , 450–461.

Cantor & Hewlett 1988). Cantor, R., & Hewlett, J. (1988). The economics of nuclear power. Resources and Energy, 10(4), 315–335. doi.org/10.1016/01650572(88)90009-6

Carelli, M., Petrovic, B., Mycoff C. W., Trucco, P., Ricotti, M., & Locatelli, G. (2007). Smaller sized reactors can be economically attractive. In Proceedings of ICAPP 2007 (p. 7569). Nice. Retrieved from https://www.researchgate.net/profile/Giorgio_Locatelli/publication/256296705_Smaller_sized_reactors_can_be_economically_attractive/links/00b7d52237ac23f85d000000.pdf

Carelli, M., Garrone, P., Locatelli, G., Mancini, M., Mycoff, M., Trucco, P., & Ricotti, M. (2010). Economic features of integral, modular, small-to-medium size reactors. Progress in Nuclear Energy, 403-414.

Carelli, M. D., & Ingersoll, D. T. (2014). Handbook of small modular nuclear reactors. Handbook of Small Modular Nuclear Reactors. doi.org/10.1016/C2013-0-16379-9

Carelli, M., Petrovic, B., Mycoff C. W., Trucco, P., Ricotti, M., & Locatelli, G. (2007). Smaller sized reactors can be economically attractive. In Proceedings of ICAPP 2007 (p. 7569). Nice. Retrieved from https://www.researchgate.net/profile/Giorgio_Locatelli/publication/256296705_Smaller_sized_reactors_can_be_economically_attractive/links/00b7d52237ac23f85d000000.pdf

Cooper, M. (2014). Small modular reactors and the future of nuclear power in the United States. Energy Research & Social Science, 3, 161–177. doi.org/10.1016/J.ERSS.2014.07.014

Darling, S. B., You, F., Veselka, T., & Velosa, A. (2011). Assumptions and the levelized cost of energy for photovoltaics. Energy & Environmental Science, 4(9), 3133. doi.org/10.1039/c0ee00698j

De Roo, G., & Parsons, J. (2011). A Methodology for Calculating the Levelised Cost of Electricity in Nuclear Power Systems with Fuel Recycling. Energy Economics, 826839.

DECC. (2013). Electricity Generation Cost Model - 2013, Update of non-renewable technologies. London. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/2236

34/2013_Update_of_Non-Renewable_Technologies_FINAL.pdf

Doloi, H.K. (2011). Understanding stakeholders' perspective on cost estimation in project management. International Journal of Project Management, Pg. 622-636. doi.org/10.1016/j.ijproman.2010.06.001

DTI. (2007). The Future of Nuclear Power. London. Retrieved from http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/files/file39199.pdf

EIA. (2016). Levelized Cost and Levelized Avoided Cost of New Generation. Washington DC: US Energy Information Administration.

EWMG. (2007). Cost Estimating Guidelines for Generation IV Nuclear Energy Systems.

Retrieved from https://www.gen-4.org/gif/upload/docs/application/pdf/201309/emwg_guidelines.pdf

Feretic & Tomsic (2005); Feretic, D., & Tomic, Z. (2005). Probabilistic Analysis of Electrical Energy Costs Comparing: Production Costs for Gas, Coal and Nuclear Power Plants. Energy Policy. Pg. 5-13.

Franek, J., & Kresta, A. (2014). Judgment Scales and Consistency Measure in AHP. Procedia Economics and Finance, 12, 164–173. doi.org/10.1016/S22125671(14)00332-3

Gross, R., Blyth, W., & Heptonstall, P. (2010). Risks, revenues and investment in electricity generation: Why policy needs to look beyond costs. Energy Economics, 32(4), 796–804. doi.org/10.1016/j.eneco.2009.09.017

Grubler, A. (2010). The Costs of the French Nuclear Scale-up: A Case of Negative Learning By Doing. Energy Policy. Pg. 5174 - 5188.

Hall, S. (2004). Nuclear Plant Life Cycle Cost Analysis Considerations. Proceedings of ICAPP ’04. Paper 4072. USA

Harris, G., Heptonstall, P., Gross, R., & Handley, D. (2013). Cost estimates for nuclear power in the UK. Energy Policy, 62, 431–442. doi.org/10.1016/j.enpol.2013.07.116

Hewlett, J.G. (1992). The Operating Costs and Longevity of Nuclear Power Plants: Evidence from the USA. Energy Policy. Pg. 608-622.

Hidayatullah, H., Susyadi, S., & Subki, M. H. (2015). Design and technology development for small modular reactors - Safety expectations, prospects and impediments of their deployment. Progress in Nuclear Energy, 79, 127–135. doi.org/10.1016/j.pnucene.2014.11.010

IAEA. (2006). Economic Performance Indicators for Nuclear Power Plants. Vienna. Retrieved from http://www-pub.iaea.org/MTCD/Publications/PDF/TRS437_web.pdf

IEA. (2015). Projected Costs of Generating Electricity 2015 Edition. Paris: OECD.

Ingersoll, D. T. (2009). Deliberately small reactors and the second nuclear era. Progress in Nuclear Energy, 51(4–5), 589–603. doi.org/10.1016/J.PNUCENE.2009.01.003

Kahraman, C., Ertay, T., & Büyüközkan, G. (2006). A fuzzy optimization model for QFD planning process using analytic network approach. European Journal of Operational Research, 171(2), 390–411. doi.org/10.1016/j.ejor.2004.09.016

Kennedy, D. (2007). New nuclear power generation in the UK: Cost benefit analysis. Energy Policy, 3701–3716.

Kessides, I. N. (2010). Nuclear power: Understanding the economic risks and uncertainties. Energy Policy, 38(8), 3849–3864. doi.org/10.1016/j.enpol.2010.03.005

Kidd, S.W. (2013). Nuclear power - Economics and public acceptance. Energy Strategy Reviews. 1(4), 277-281. doi.org/10.1016/j.esr.2013.03.006

Koomey, J., & Hultman, N. E. (2007). A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005. Energy Policy, 35(11), 5630–5642. doi.org/10.1016/J.ENPOL.2007.06.005

Kula, E. (2015). Future generations and nuclear power—A pluralistic economic appraisal. Futures, 73, 37–47. doi.org/10.1016/j.futures.2015.08.001

Lanjewar, P. B., Rao, R. V., Kale, A. V., Taler, J., & Ocłoń, P. (2016). Evaluation and selection of energy technologies using an integrated graph theory and analytic hierarchy process methods. Decision Science Letters, 327–348. doi.org/10.5267/j.dsl.2015.10.001

Lazard. (2015). Lazard's Levelized Cost of Energy Analysis.

Lévêque, F. (2013). Estimating the costs of nuclear power: benchmarks and uncertainties. Retrieved from https://hal.archives-ouvertes.fr/hal-00782190/

Levi, P., & Pollitt, M. (2015). Cost trajectories of low carbon electricity generation technologies in the UK: A study of cost uncertainty. Enegy Policy, 48-59.

Li, MK., Liu, YK., Peng, MJ., Xie, CL., & Yang,LQ. (2016). The decision making method of task arrangement based on analytic hierarchy process for nuclear safety in radiation field. Progress in Nuclear Energy, 93, 318-326. doi.org/10.1016/j.pnucene.2016.09.006

Lin, X., Christabel, M.F., Ho, G., & Shen, Q.P. (2017). Who should take the responsibility? Stakeholders' power over social responsibility issues in construction projects. Journal of Cleaner Production. 154. 318-329.

Linares, P., & Conchado, A. (2013). The economics of new nuclear power plants in liberalized electricity markets. Energy Economics, 40, S119–S125. doi.org/10.1016/J.ENECO.2013.09.007

Locatelli, G., Bingham, C., & Mancini, M. (2014). Small modular reactors: A comprehensive overview of their economics and strategic aspects. Progress in Nuclear Energy, 73, 75–85. https://doi.org/10.1016/j.pnucene.2014.01.010

Locatelli, G., & Mancini, M. (2010). Competitiveness of Small-Medium, New Generation Reactors: A Comparative Study on Decommissioning. Journal of Engineering for Gas Turbines and Power, 132(10), 102906. doi.org/10.1115/1.4000613

Locatelli, G., & Mancini, M. (2011). The role of the reactor size for an investment in the nuclear sector: An evaluation of non-financial parameters. Progress in nuclear energy, 53(2) 212-222. doi.org/10.1016/j.pnucene.2010.10.002

Locatelli, G., & Mancini, M. (2012a). A framework for the selection of the right nuclear power plant. International Journal of Production Research, 50(17), 4753–4766. doi.org/10.1080/00207543.2012.657965

Locatelli, G., & Mancini, M. (2012b). A framework for the selection of the right nuclear power plant. International Journal of Production Research, 50(17), 4753–4766. doi.org/10.1080/00207543.2012.657965

Luzon, B., & El-Sayegh, S. M. (2016). Evaluating supplier selection criteria for oil and gas projects in the UAE using AHP and Delphi. International Journal of Construction Management, 16(2), 175–183. doi.org/10.1080/15623599.2016.1146112

MacKerron, G. (1992). Nuclear costs: Why do they keep rising? Energy Policy, 641-652.

Magwood IV, WD., & Paillere, H. (2017). Looking ahead at reactor development. Progress in Nuclear Energy, 102, 58-67. doi.org/10.1016/j.pnucene.2017.07.001

Mari, C. (2014). The costs of generating electricity and the competitiveness of nuclear power. Progress in Nuclear Energy, 73, 153–161. doi.org/10.1016/j.pnucene.2014.02.005

Marltunen, M., Lienert, J., & Belton, V (2017). Structuring problems for Multi-Criteria Decision Analysis in practice: A literature review of method combinations. European Journal of Operational Research. 263(1) 1-17

Maronati, G., Petrovic, B., Van Wyk, J. J., Kelley, M. H., & White, C. C. (2018). EVAL: A methodological approach to identify NPP total capital investment cost drivers and sensitivities. Progress in Nuclear Energy, 104, 190–202. doi.org/10.1016/J.PNUCENE.2017.09.014

Meade, L. M., & Presley, A. (2002). R&D project selection using the analytic network process. IEEE Transactions on Engineering Management, 49(1), 59–66. doi.org/10.1109/17.985748

MIT. (2003). The Future of Nuclear Power. Massachusetts Institute of Technology. ISBN 0-615- 12420-8

MIT. (2009). Update to the future cost of nuclear power . Cambridge, MA: MIT.

Mott MacDonald. (2010). UK Electricity Generation Costs Update. Mott MacDonald. Brighton.

NREL (2012). Cost and performance data for power generation technologies, NREL, Black & Veach Corporation, Feb 2012

ORNL (2003). U.S. Nuclear Power Plant Operating Cost and Experience Summaries. ORNL/TM-2003/219.

Palacios, J., Alonso, G., Ramirez, R., Gomez, A., Ortiz, J., & Longoria, L. (2004). Levelized Costs for Nuclear, Gas and Coal for Electricity, under the Mexican Scenario. Americas Nuclear Energy Symposium (ANES 2004). Miami: Department of Energy

Pannier, C. P., & Skoda, R. (2014). Comparison of Small Modular Reactor and Large Nuclear Reactor Fuel Cost. Energy and Power Engineering, 6, 82–94. doi.org/10.4236/epe.2014.65009

Ramana, M. V, & Mian, Z. (2014). One size doesn’t fit all: Social priorities and technical conflicts for small modular reactors. Energy Research and Social Science, 2, 115–124. doi.org/10.1016/j.erss.2014.04.015

Read, L., Madani, K., Mokhtari, S., & Hanks, C. (2017). Stakeholder-driven multiattribute analysis for energy project selection under uncertainty. Energy. 119. 744-753. doi.org/10.1016/j.energy.2016.11.030

Riesz, J., Sotiriadis, C., Vithayasrichareon, P., & Gilmore, J. (2017). Quantifying key uncertainties in the costs of nuclear power. International Journal of Energy Research, 41(3), 389–409. doi.org/10.1002/er.3618

Roques, F.A., Nuttall, W.J., Newbery, D.M., de Neufville, R., Connors, S. (2006) Nuclear Power: A Hedge against Uncertain Gas and Carbon Prices? The Energy Journal Vol. 27, No. 4 (2006), pp. 1-23

Roth, I.F. & Ambs, L.L. (2004) Incorporating Externalities into a Full Cost Approach to Electric Power Generation Life-cycle Costing. Energy. Pg. 2125-2144.

Rothwell, G. (2006). A Real Options Approach to Evaluating New Nuclear Power Plants. The Energy Journal Vol. 27, No. 1, pp. 37-53

Saaty, R. W. (1987). The analytic hierarchy process—what it is and how it is used. Mathematical Modelling, 9(3–5), 161–176. doi.org/10.1016/0270-0255(87)90473-8

Saaty, T. L. (2001). Analytic Network Process. In Encyclopedia of Operations Research & Management Science (pp. 28–35). Dordrecht: Kluwer Academic Publishers. doi.org/10.1007/1-4020-0611-X_32

Settanni, E., Newnes, L. B., Thenent, N. E., Parry, G., & Goh, Y. M. (2014). A throughlife costing methodology for use in product-service-systems. International Journal of Production Economics, 153, 161–177. doi.org/10.1016/j.ijpe.2014.02.016

Shin, D.-W., Shin, Y., & Kim, G.-H. (2016). Comparison of Risk Assessment for a Nuclear Power Plant Construction Project Based on Analytic Hierarchy Process and Fuzzy Analytic Hierarchy Process. Journal of Building Construction and Planning Research, 4(3), 157–171. doi.org/10.4236/jbcpr.2016.43010

Smyth, H., Lecouevre, L., & Vaesken, P. (2018). Co-creation of value and the project context: Towards application on the case of Hinkley Point C nuclear power station. International Journal of Project Management.

Söderholm, K., Tuunanen, J., Amaba, B., Bergqvist, S., & Lusardi, P. (2014). Licensing process characteristics of Small Modular Reactors and spent nuclear fuel repository. Nuclear Engineering and Design, 276, 1–8. doi.org/10.1016/J.NUCENGDES.2014.05.035

Sovacool, B. K. (2010). A Critical Evaluation of Nuclear Power and Renewable Electricity in Asia. Journal of Contemporary Asia, 40(3), 369–400. doi.org/10.1080/00472331003798350

Thomas, S. (2005). The economics of nuclear power: analysis of recent studies. Public Services International Research Unit (PSIRU). Retrieved from www.psiru.org

University of Chicago. (2004). The Economic Future of Nuclear Power. https://www.eusustel.be/public/documents_publ/links_to_docs/cost/uoc-study.pdf

Vazquez, A., & Iglesias, G. (2016). Grid parity in tidal stream energy projects: An assessment of financial, technological and economic LCOE input parameters. Technological Forecasting and Social Change, 89-101

Vegel, B., & Quinn, J. C. (2017). Economic evaluation of small modular nuclear reactors and the complications of regulatory fee structures. Energy Policy, 104, 395–403. doi.org/10.1016/j.enpol.2017.01.043

World Nuclear News. (2016). Future Unclear for US Unit Despite Auction Success. http://www.world-nuclear-news.org/C-Future-unclear-for-US-unit-despite-auctionsuccess-1804168.html Accessed 18/04/2016